CERN

Accelerator Physics

Lecture 1 of 2

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Topics for Today

- The CERN Accelerator Complex
- Main Steps in the LHC Beam Production
- Transverse Motion

Topics for Tomorrow

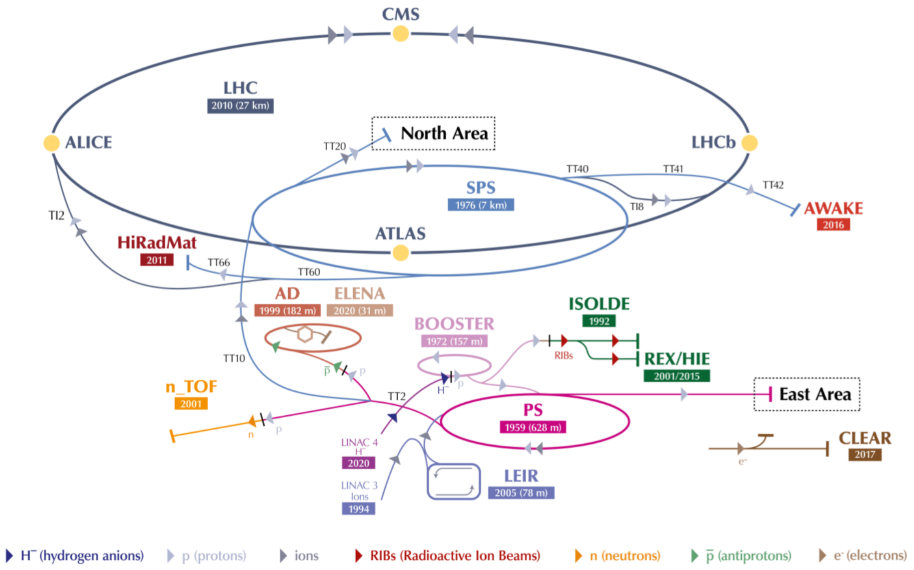
- Longitudinal Motion
- Some Possible Limitations
- On the Way to HL-LHC…

The CERN Accelerator Complex

The LHC and its Injector Complex

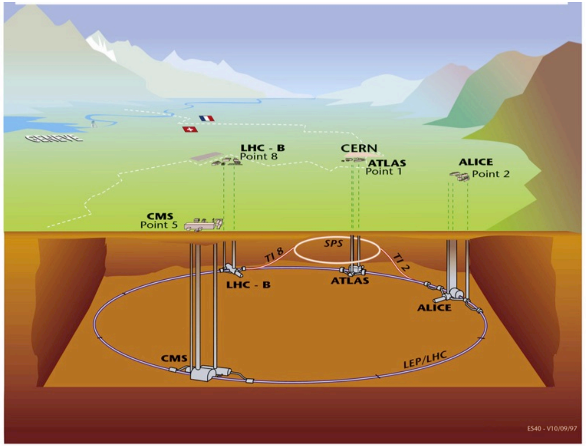
- The LHC performance is largely determined by injector complex performance
  - **Beam Quality → Beam Brightness**

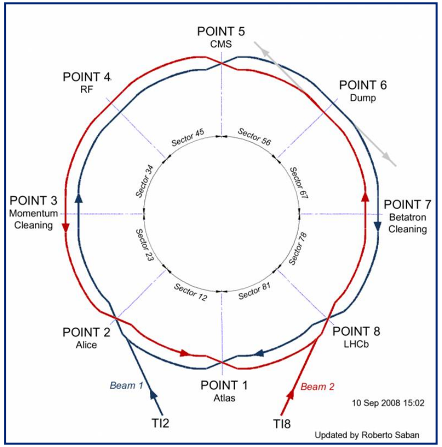
- The **PSB** determines initial beam **brightness**
- The **PS** determines the **timing structure**
  - 25ns, 50ns, BCMS, 8b4e, …
- The **SPS** boosts the energy and creates **bunch trains**

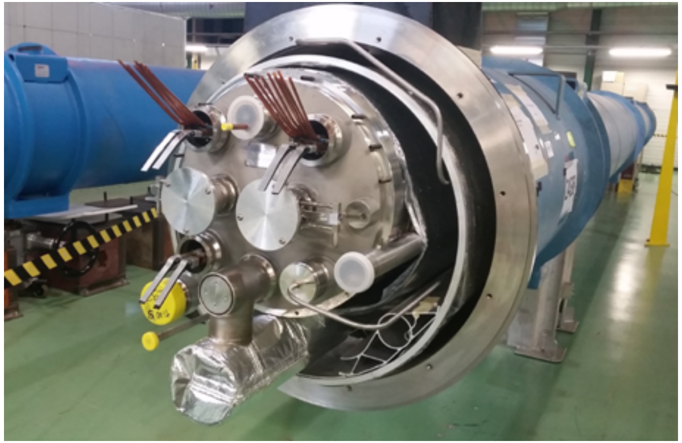


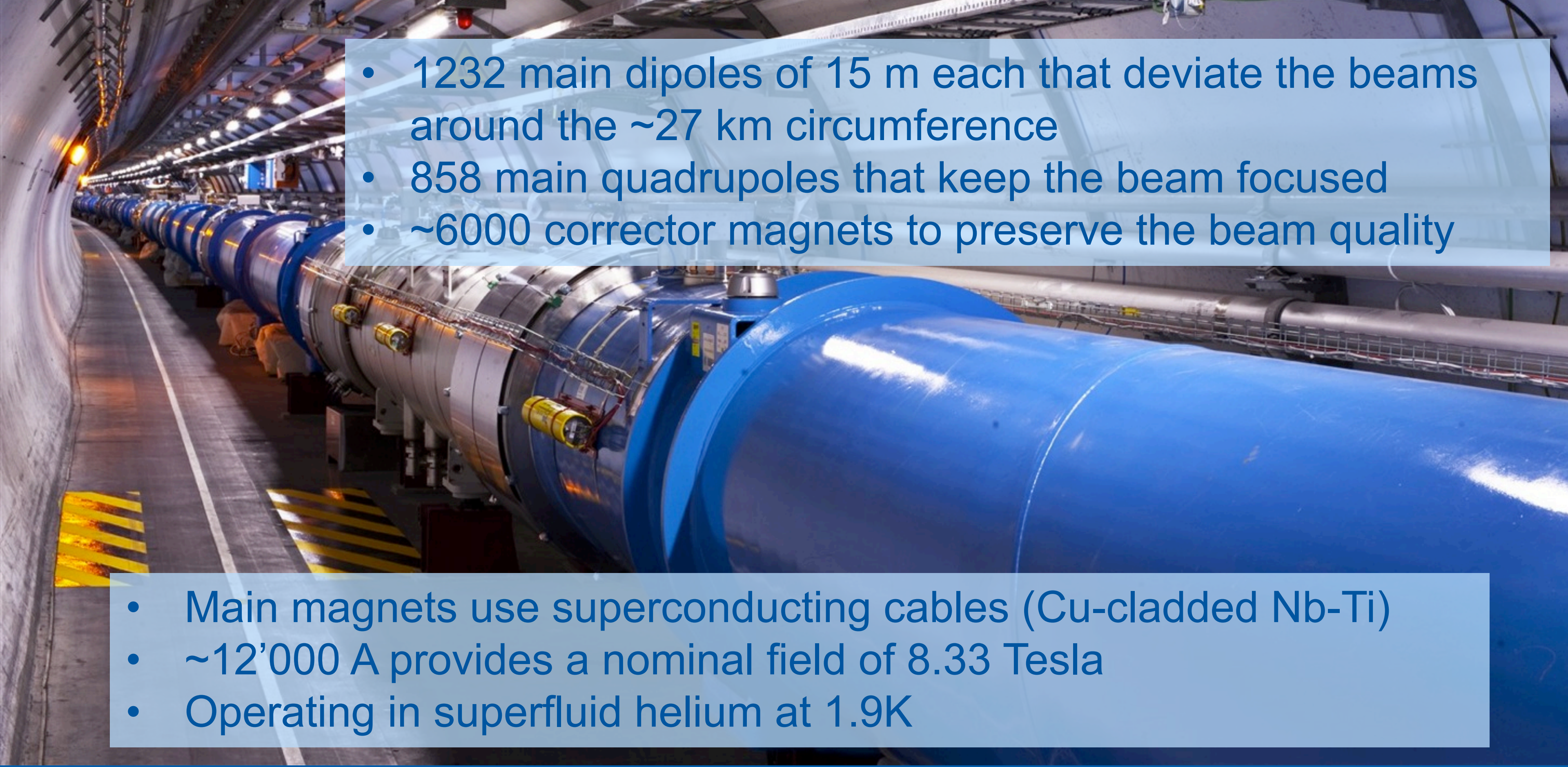
Large Hadron Collider -LHC

- Situated on average ~100 m under ground housing the four major experiments
- Circumference 26.7 km
- Two separate beam pipes going through the same cold mass 19.4 cm apart
- 150 tonnes of liquid helium to keep the magnets cold and superconducting





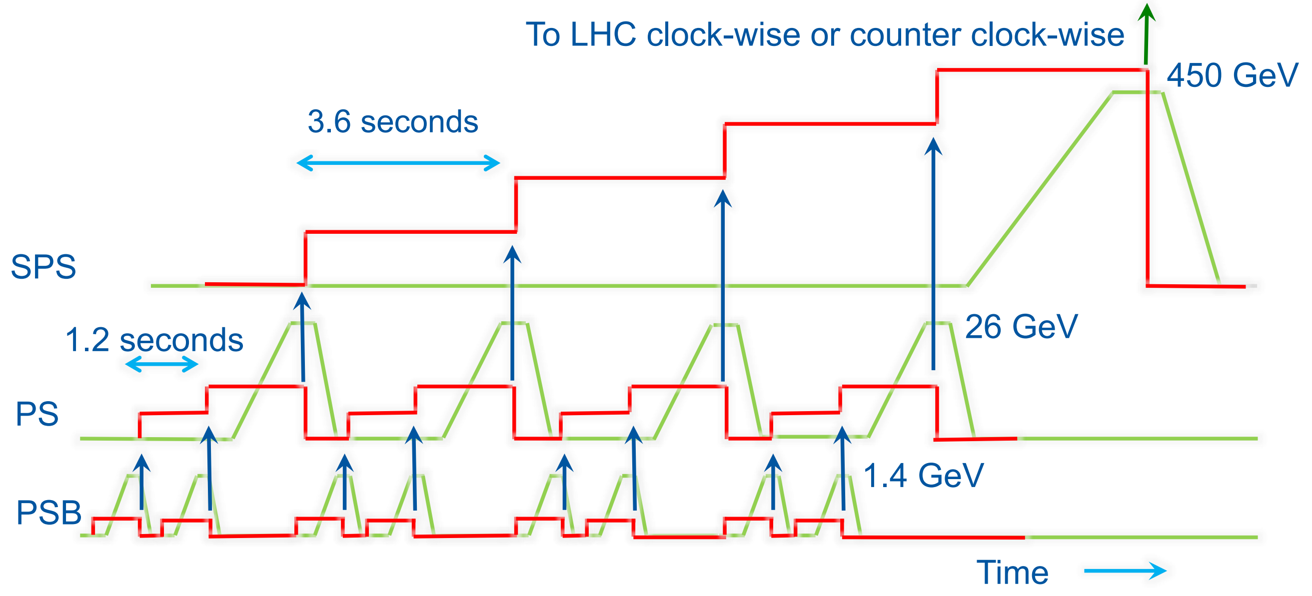




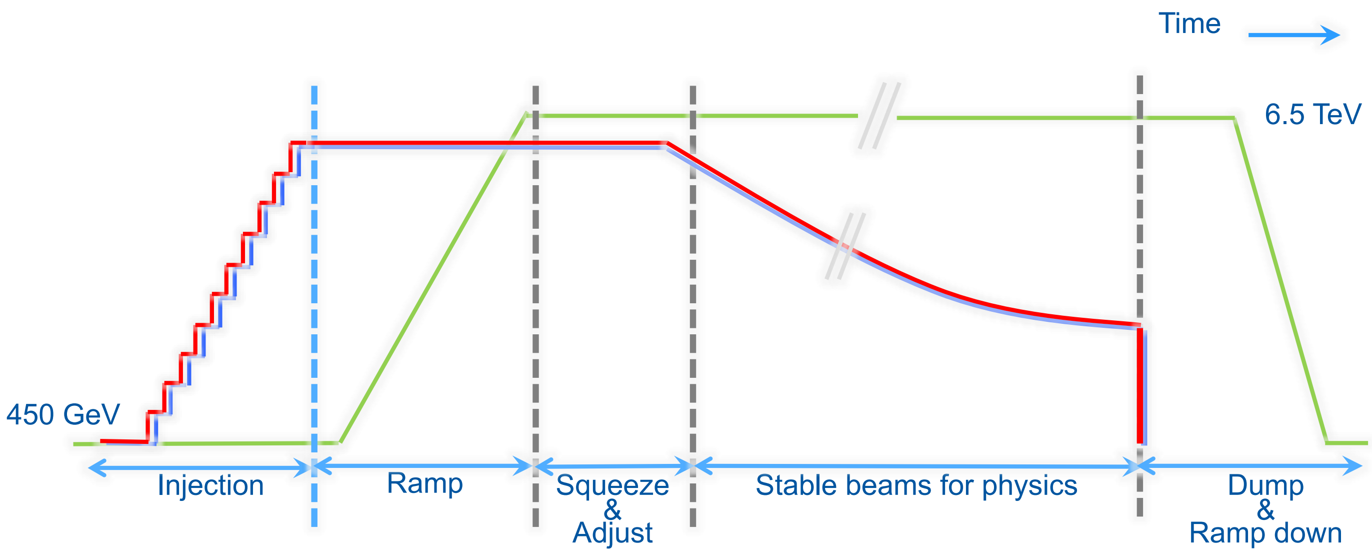
- 1232 main dipoles of 15 m each that deviate the beams around the ~27 km circumference
- 858 main quadrupoles that keep the beam focused
- ~6000 corrector magnets to preserve the beam quality

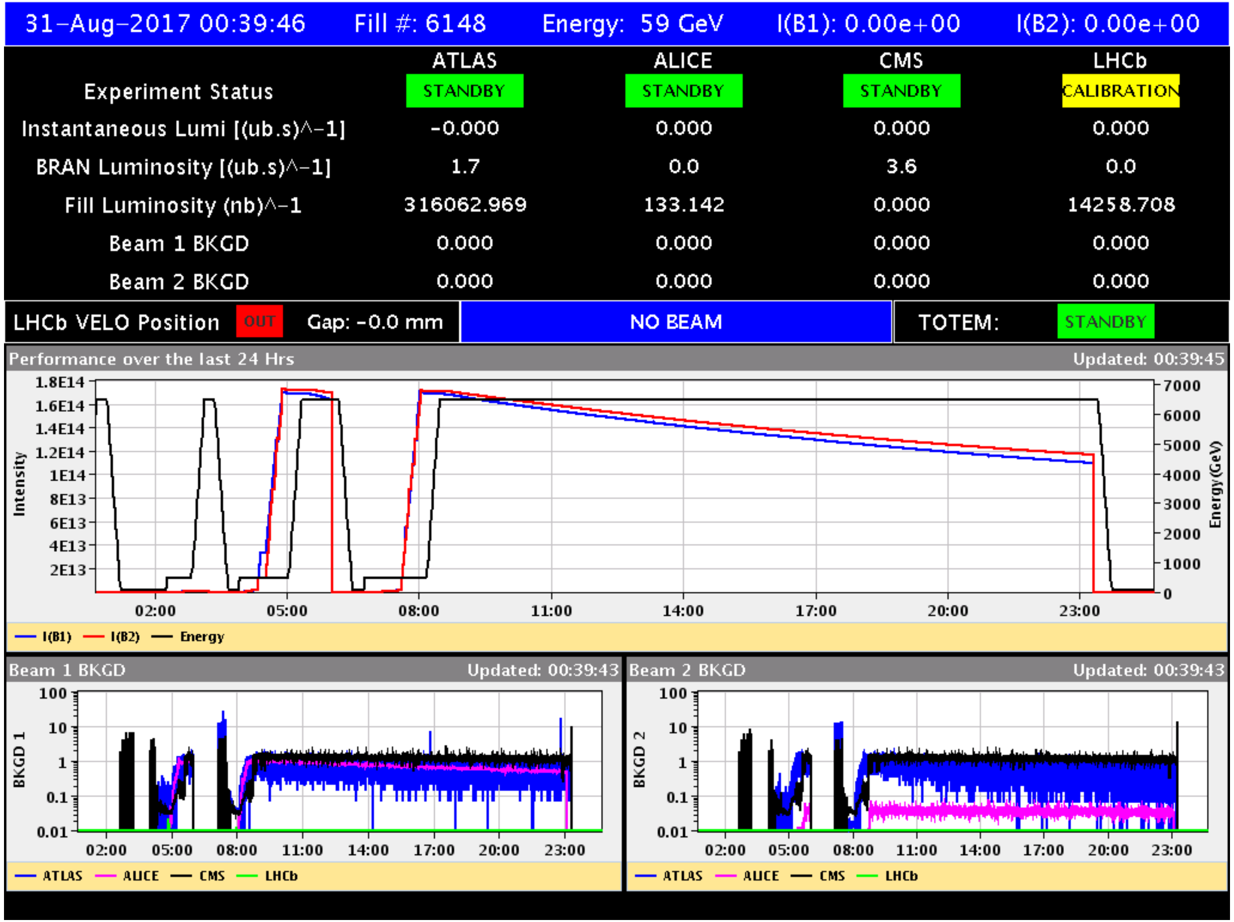
- Main magnets use superconducting cables (Cu-cladded Nb-Ti)
- ~12’000 A provides a nominal field of 8.33 Tesla
- Operating in superfluid helium at 1.9K

LHC Beam in the Injector Complex



Filling & Cycling the LHC



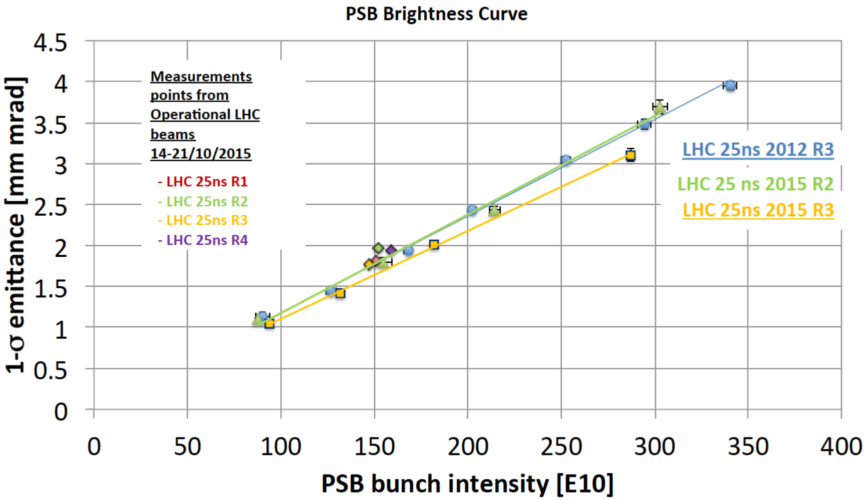

31-Aug-2017 00:39:46
Fill #: 6148
Energy: 59 GeV
I(B1): 0.00e+00
I(B2): 0.00e+00
ATLAS
ALICE
CMS
LHCb
Experiment Status
STANDBY
STANDBY
STANDBY
CALIBRATION
Instantaneous Lumi [(ub.s)^-1]
-0.000
0.000
0.000
0.000
BRAN Luminosity [(ub.s)^-1]
1.7
0.0
3.6
0.0
Fill Luminosity (nb)^-1
316062.969
133.142
0.000
14258.708
Beam 1 BKGD
0.000
0.000
0.000
0.000
Beam 2 BKGD
0.000
0.000
0.000
0.000
LHCb VELO Position
OUT
Gap: -0.0 mm
NO BEAM
TOTEM:
STANDBY
Performance over the last 24 Hrs
Updated: 00:39:45
Intensity
Energy (GeV)
I(B1)
I(B2)
Energy
Beam 1 BKGD
Updated: 00:39:43
BKGD 1
Beam 2 BKGD
Updated: 00:39:43
BKGD 2
ATLAS
ALICE
CMS
LHCb

Main Steps in the LHC Beam Production

Injection into the PSB until LS2

- With the multi-turn proton injection from Linac 2 the intensity was increased with about constant density

Equivalent for beam size

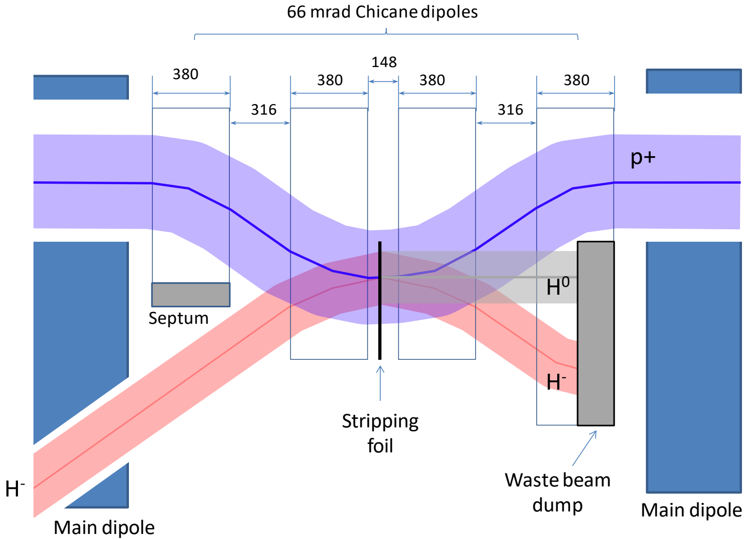


The more hose on the drum the bigger the roll

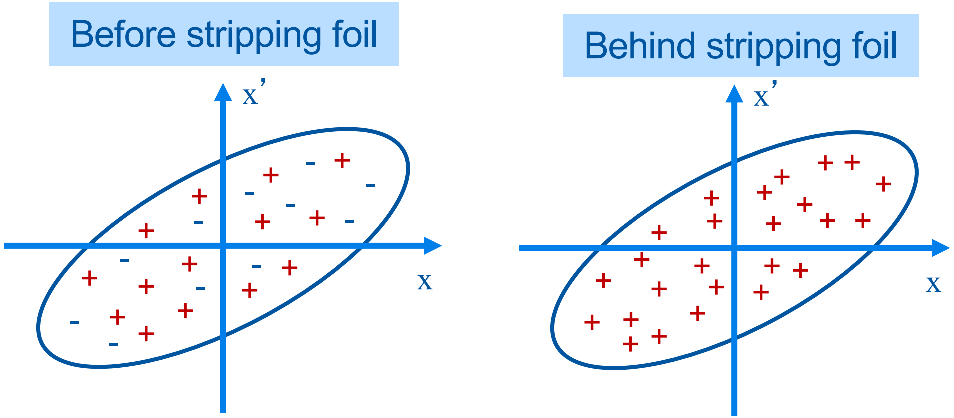
- With the new Linac 4 we can increase the density while increasing the intensity

LINAC4 & Charge Exchange Injection

Key ingredient for brighter beams



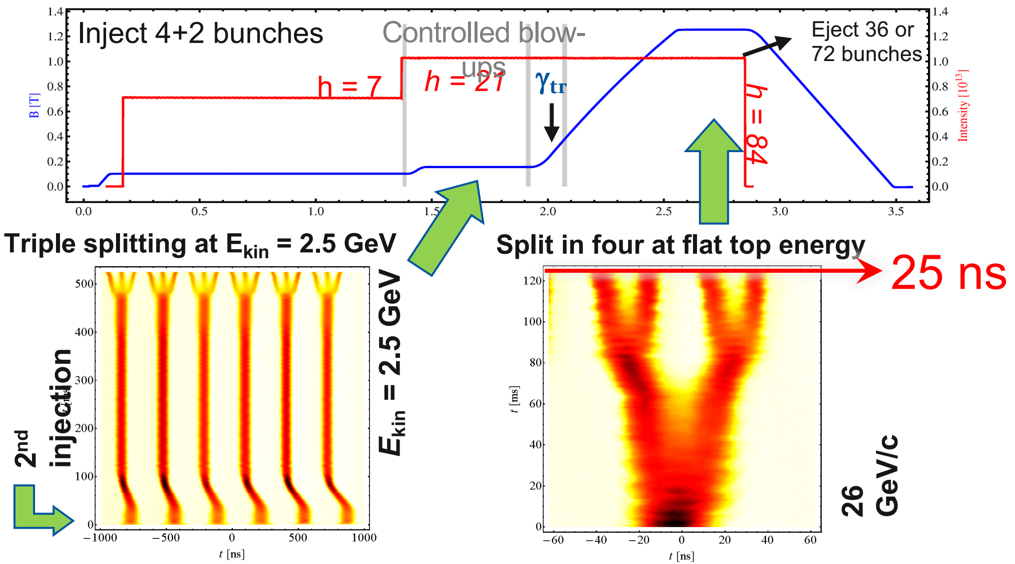
Use H⁻ beam from LINAC 4



Phase Space Painting is possible (various particle distributions)

Standard LHC 25 ns Beam in PS

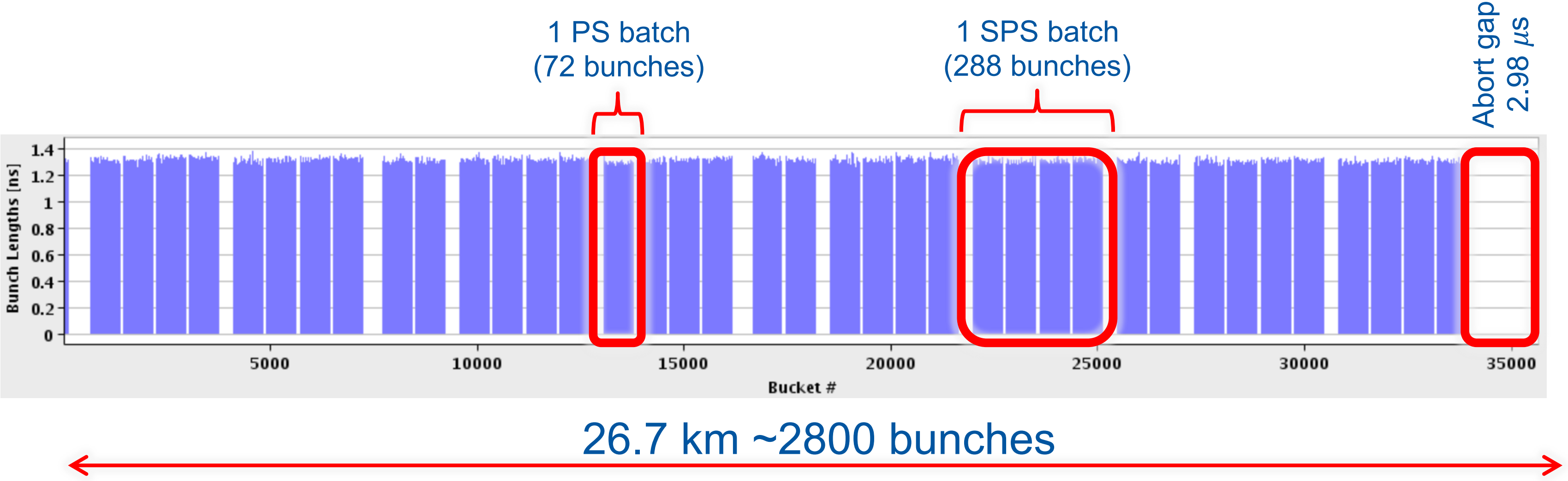
- Two injections: 4 + 2 bunches
- Triple splitting at 2.5 GeV
- Two times splitting at 26 GeV/c
- Bunch shortening through bunch rotation before extraction ➔ 4ns bunch length (4σ)
- PSB bunch intensity divided by a factor 12
  - $I_{LHC} = 1.2\text{x}10^{11}$ ppb → $I_{PSB} = 14.4\text{x}10^{11}$ ppb
- Transverse emittance determined by PSB (multi-turn injection)
- The SPS creates the bunch trains (288 bunches)



25 ns: Each PSB bunch divided by: 12 → 6 x 3 x 2 x 2 = **72**

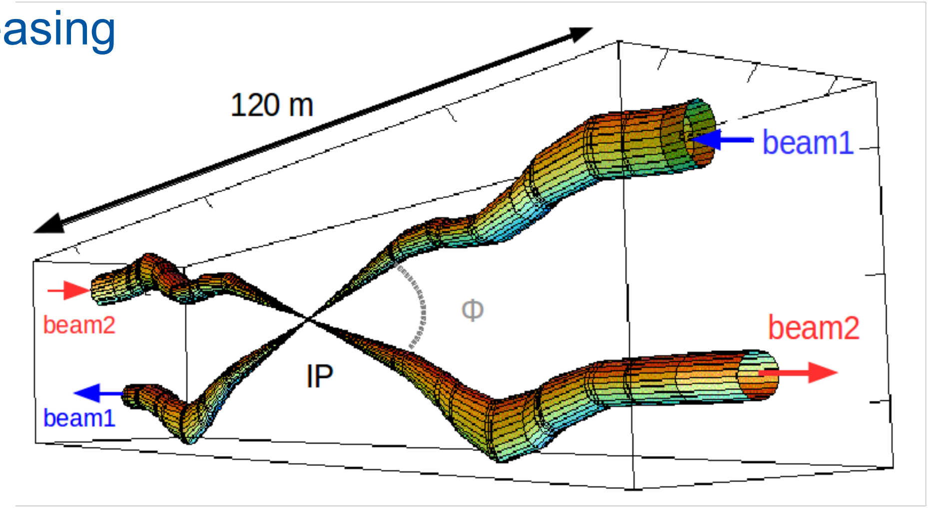
Create bunch trains in the SPS

- LHC Bunch train structure
- Up to ~ 2800 bunches per beam
- Bunch trains interrupted by injection and extraction kicker gaps.



LHC: Squeezing the Beam Size to Collide

Quadrupoles on either side of the experiments focus the beam to small dimensions, increasing the local density



Transverse Motion

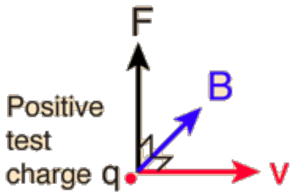
Lorentz Force

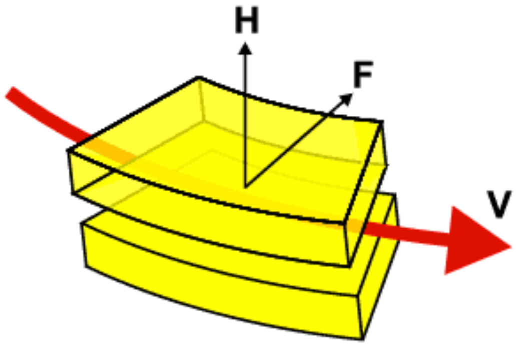
Lorentz Formula: $\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$

Electric force (under $q\vec{E}$) · *Magnetic force* (under $q\vec{v} \times \vec{B}$)

The **Transverse motion** is dominated by **magnetic forces**:

$$\vec{F} = q\vec{v} \times \vec{B}$$





dipole

Magnetic Rigidity

- The **Lorentz Force** can be seen as a **Centripetal Force** → $F = q\vec{v} \times \vec{B} = \frac{mv^2}{\rho}$
- ρ is the particle's **radius of curvature** in the magnetic field → $B\rho = \frac{mv}{q} = \frac{p}{q}$
- ***Bρ*** is the **magnetic rigidity**

$$B\rho[\mathrm{Tm}] = \frac{mv}{q} = \frac{p[\mathrm{GeV/c}]}{q} \quad \Rightarrow \quad B\rho = 3.3356\, p$$

- **Increasing the momentum** of a particle beam and keeping the **radius constant** requires **ramping the magnetic fields**

Example 1: Radius vs Radius of Curvature

- LHC circumference = 26658.883 m
  - Therefore the radius r = 4242.9 m
- There are 1232 main dipoles to make 360˚
  - This means that each dipole deviates the beam by only 0.29˚
- The dipole length = 14.3 m
  - The total dipole length is thus 17617.6 m, which occupies 66.09 % of the total circumference
- The bending radius ρ is therefore
  - $\rho = 0.6609 \times 4242.9$ m → $\rho =$ 2804 m
- Apart from dipole magnets there are also straight sections in our collider
  - These are used to house RF cavities, diagnostics equipment, special magnets for injection, extraction and of course the experiments !

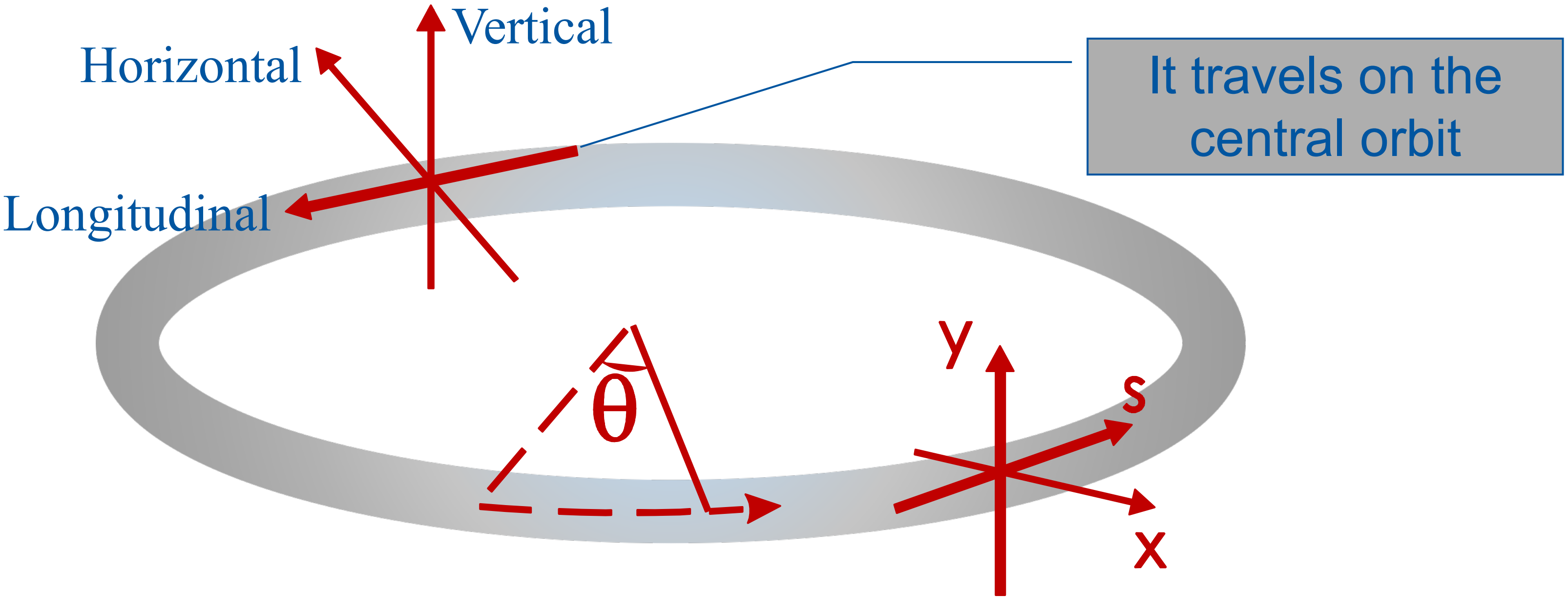
Example 2: High Energy LHC

- Use the **existing LHC tunnel** and replace existing magnets with **high field superconducting magnets**
- Beam rigidity: $B\rho = 3.3356\, p$

- **ρ = 2804 m** (fixed by tunnel geometry and filling factor)
- Vigorous R&D for **20 T dipole magnets is** on-going (Nb_3SN and HTS)

$$p = \frac{2804 \times 20}{3.3356} \Rightarrow \text{~16.5 TeV per beam} \Rightarrow \mathbf{33\ TeV_{cm}}$$

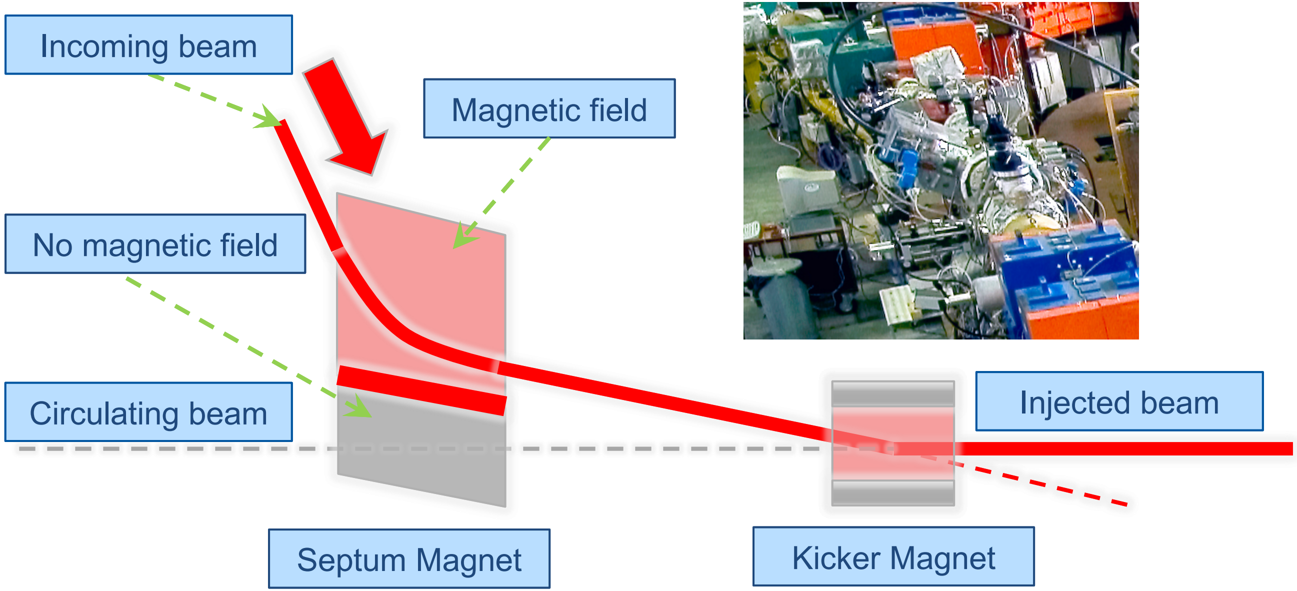
Coordinate System Used



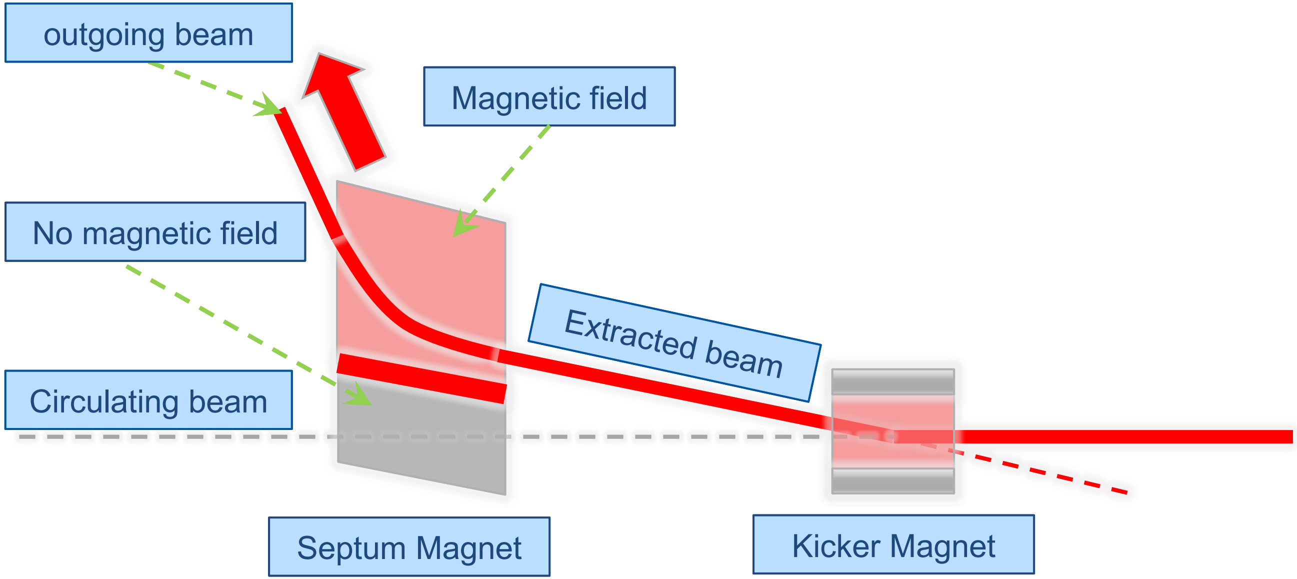
We can speak of a: **Rotating Cartesian Co-ordinate System**

LEIR as an Example

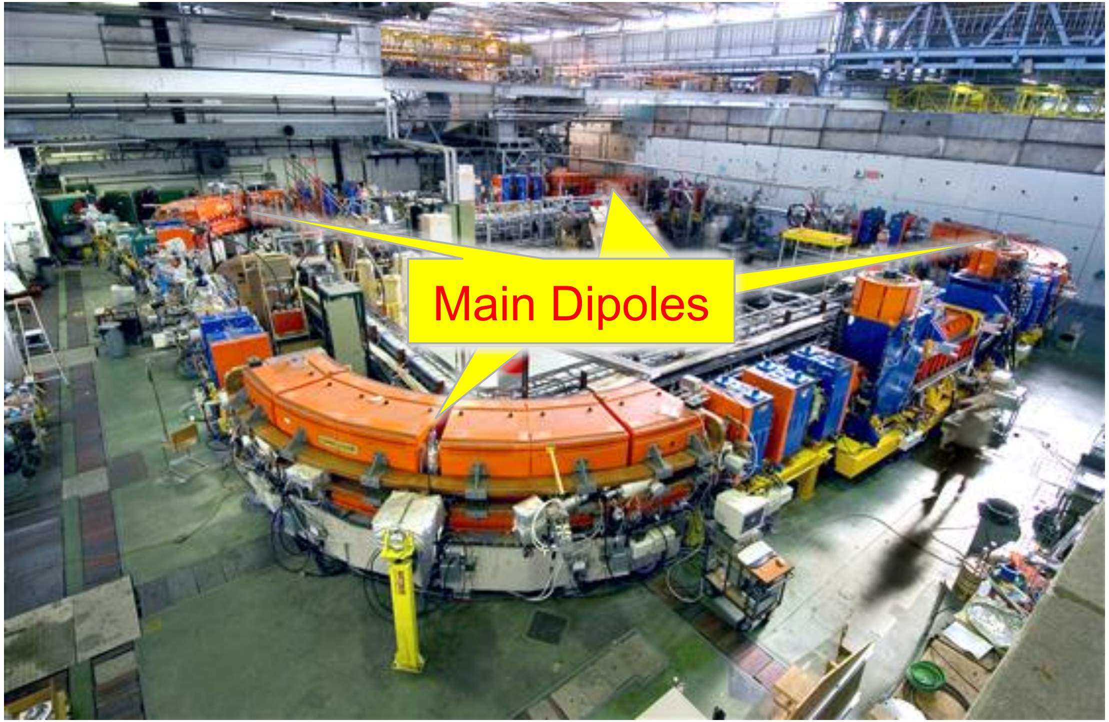
Injecting & Extracting Particles



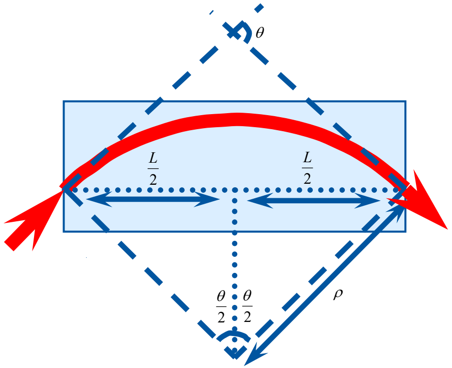
Injecting & **Extracting** Particles

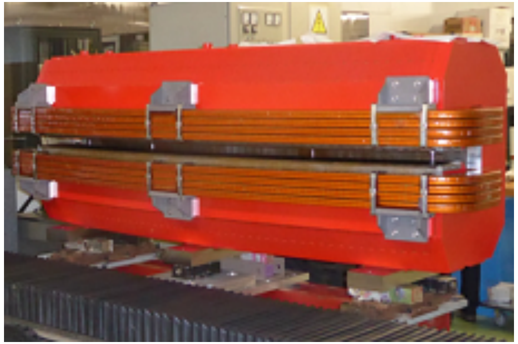


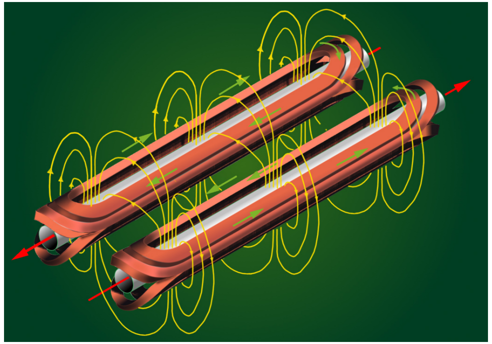
Make Particles Circulate



Dipole Magnet





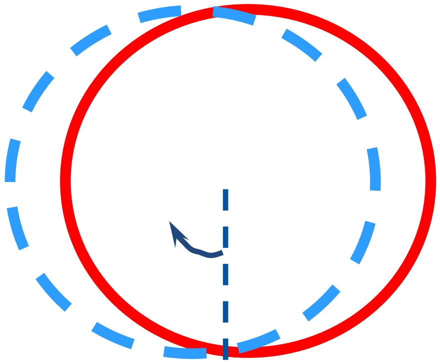


- A magnet with a uniform dipolar field deviates a particle by an angle θ in one plane
- The angle θ depends on the length L and the magnetic field B.

$$\sin\left(\frac{\theta}{2}\right) = \frac{L}{2\rho} = \frac{1}{2}\frac{LB}{(B\rho)} \quad \Rightarrow \quad \sin\left(\frac{\theta}{2}\right) = \frac{\theta}{2} \quad \Rightarrow \quad \theta = \frac{LB}{(B\rho)}$$

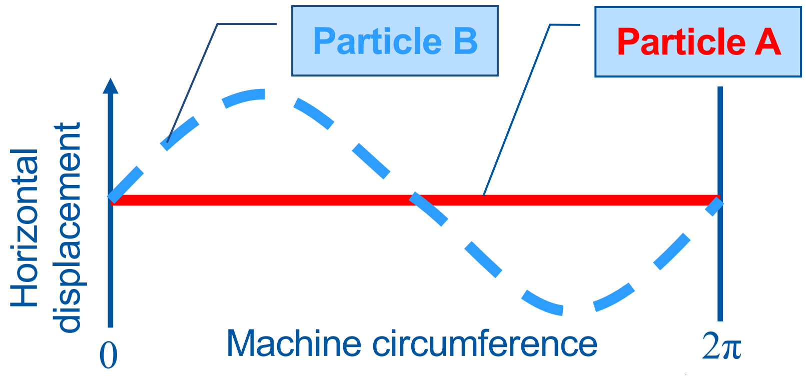
Multiple Particle in a Dipole Field

Two charged Particles in a homogeneous magnetic field



Particle B | Particle A

Horizontal motion

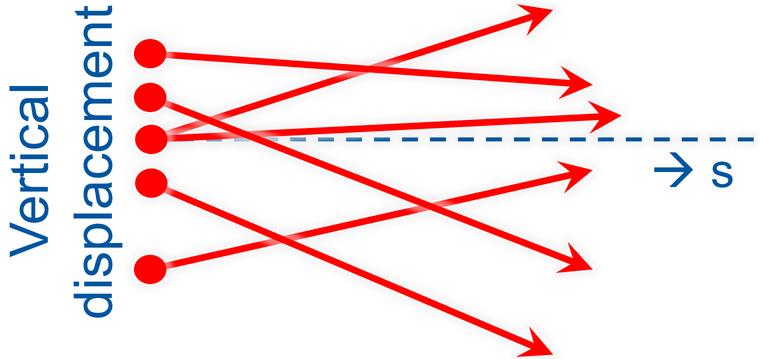


Different particles with different initial conditions in a homogeneous magnetic field will follow a closed orbit in the horizontal plane

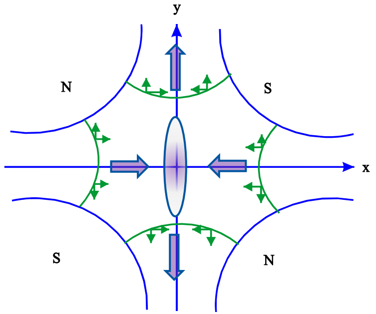
What About the Vertical Plane ?

The horizontal motion seems to be “stable”…. What about the vertical plane ?

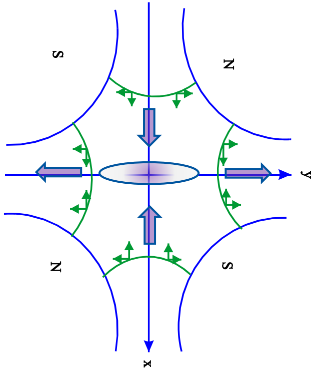
Many particles many initial conditions



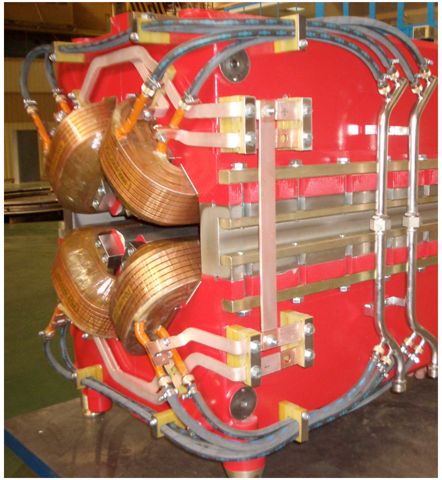
Focussing Particle Beams



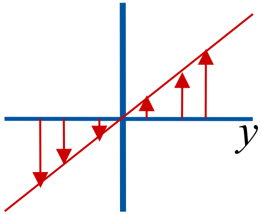
Focusing Quadrupole



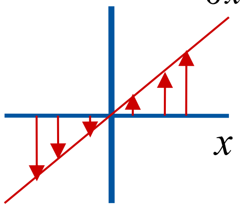
De-focusing Quadrupole



$$B_x = \frac{\partial B_x}{\partial y} y$$



$$B_y = \frac{\partial B_y}{\partial x} x$$



Field **gradient**

$$K = \frac{\partial B_y}{\partial x} [Tm^{-1}]$$

$$k = \frac{K}{B\rho} [m^{-2}]$$

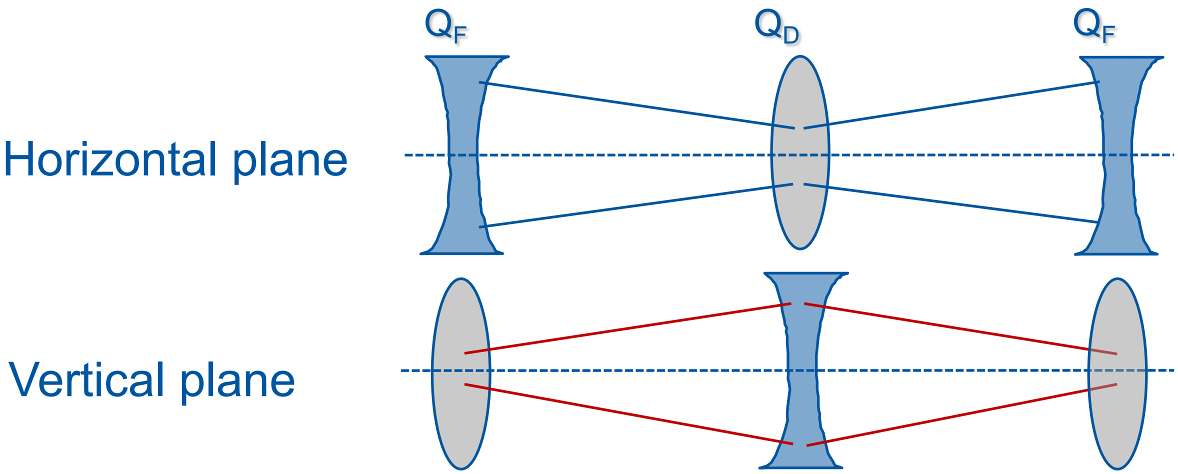
Normalised gradient

FODO Cell

- Using a combination of focusing (Q_F) and defocusing (Q_D) quadrupoles solves our problem of ‘unstable’ vertical motion.
- It will keep the beams focused in **both planes** when the position in the accelerator, type and strength of the quadrupoles are well chosen.
- By now our accelerator is composed of:
  - **Dipoles**, constrain the beam to some closed path (orbit).
  - **Focusing and Defocusing Quadrupoles**, provide horizontal and vertical focusing in order to constrain the beam in transverse directions.
- A combination of focusing and defocusing sections that is very often used is the so called: **FODO lattice**.
- This is a configuration of magnets where focusing and defocusing magnets alternate and are separated by non-focusing drift spaces.

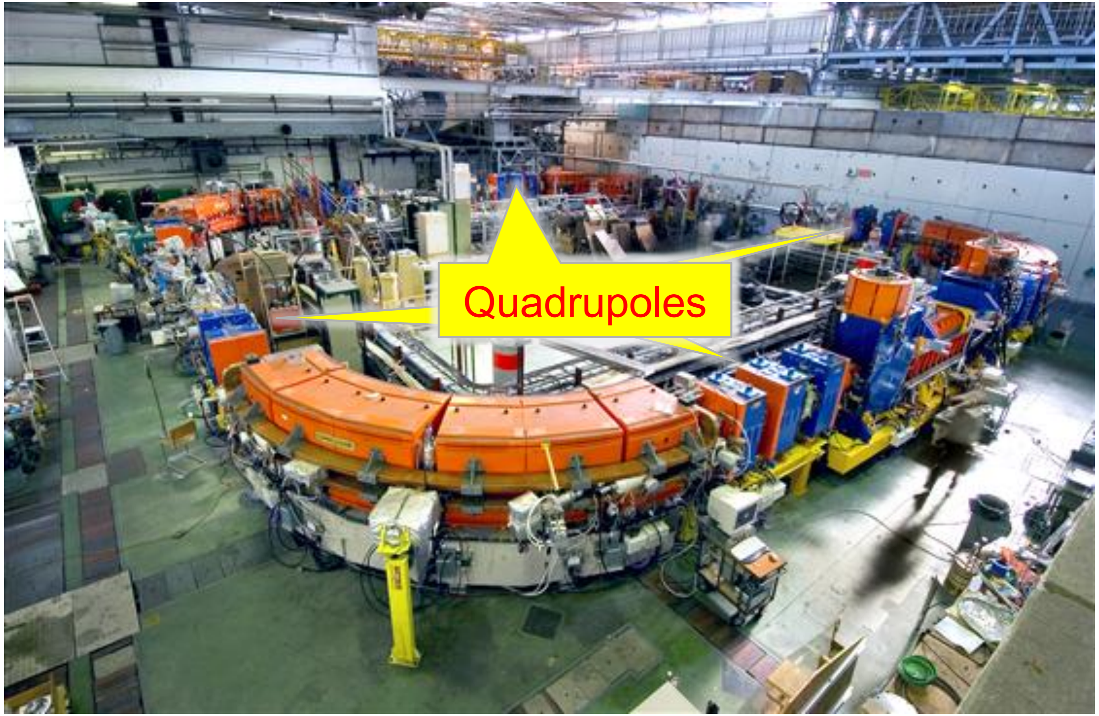
FODO Lattice

A quadrupole is defined focusing if it is oriented to focus in the horizontal plane and defocusing if it defocusses in the horizontal plane



This arrangement gives rise to **Betatron oscillations** within an envelope

Focussing Particle Beams



Hill's Equation

- These **betatron oscillations** exist in both **horizontal** and **vertical** planes.
- The **number of betatron oscillations per turn** is called the **betatron tune** and is defined as Q_x and Q_y or also Q_h and Q_v
- Hill's equation describes this motion mathematically

$$\boxed{\frac{d^2x}{ds^2} + K(s)x = 0}$$

- If the restoring force, K is constant in 's' then this is just a **Simple Harmonic Motion** (Like a pendulum)
- 's' is the longitudinal displacement around the accelerator

General Solutions of Hill's Equation

Position: $$x(s) = \sqrt{\varepsilon\beta_s}\cos(\varphi(s) + \varphi)$$

Angle: $$x' = -\alpha\sqrt{\varepsilon/_\beta}\cos(\varphi) - \sqrt{\varepsilon/_\beta}\sin(\varphi)\varphi$$

- ε and φ are constants determined by the initial conditions
- β(s) is the periodic envelope function given by the lattice configuration

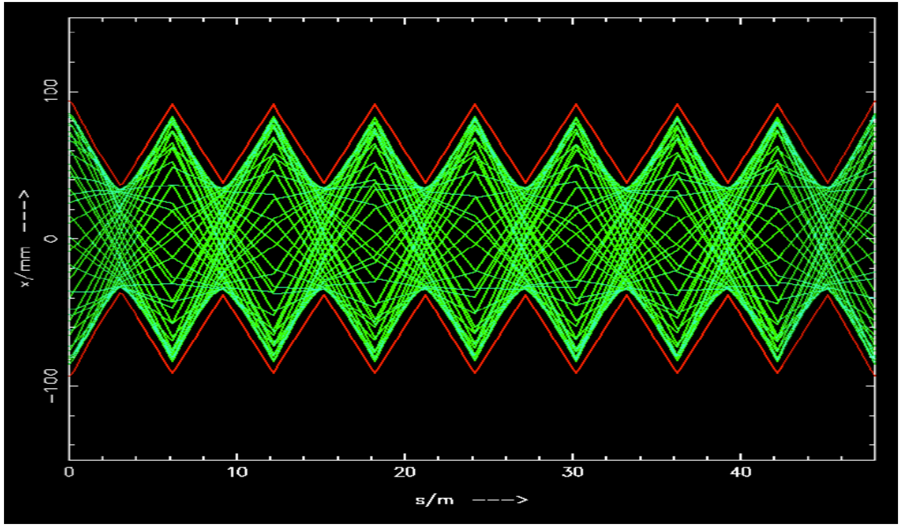
$$\varphi(s) = \int_0^s \frac{ds}{\beta(s)}$$

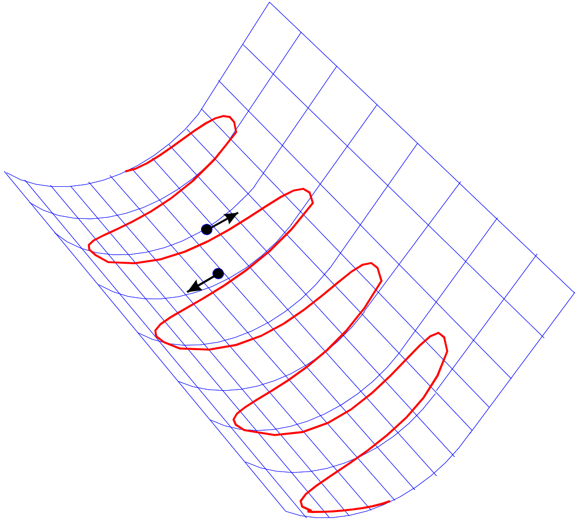
- φ(s) Is the phase advance over 1 turn around the machine

$$Q_{x/y} = \frac{1}{2\pi}\int_0^{2\pi} \frac{ds}{\beta_{x/y}(s)}$$

- Q_x and Q_y are the horizontal and vertical tunes: the number of oscillations per turn around the machine

β-function and individual particles

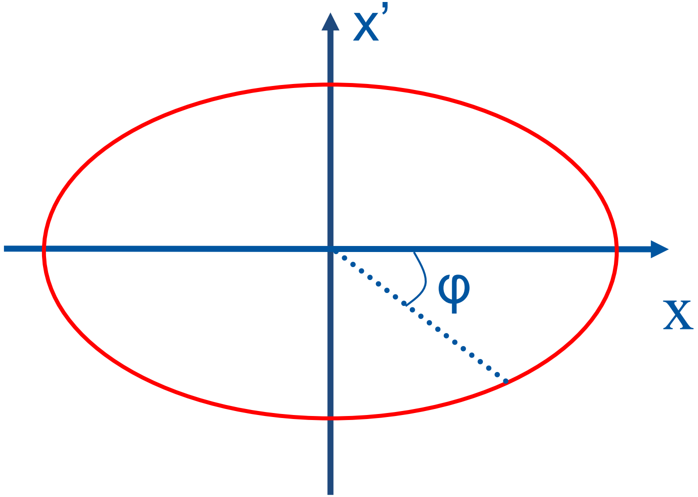


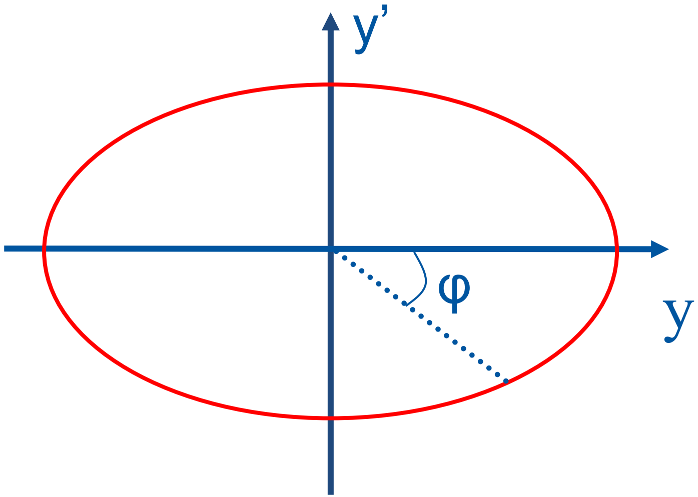


- The β-function is the envelope function within which all particles oscillate
- The shape of the β-function is determined by the lattice

Transverse Phase Space

We distinguish motion in the Horizontal & Vertical Plane

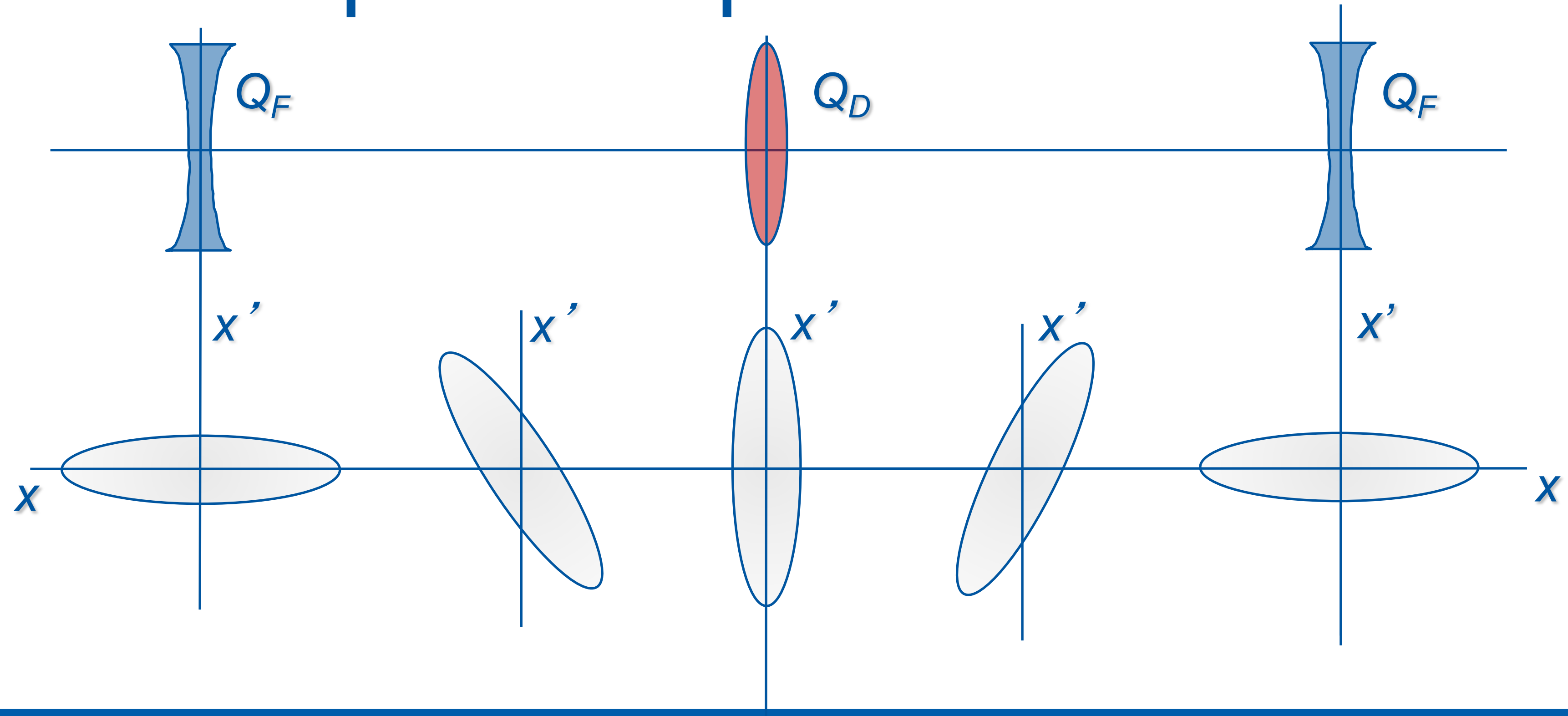




Horizontal Phase Space

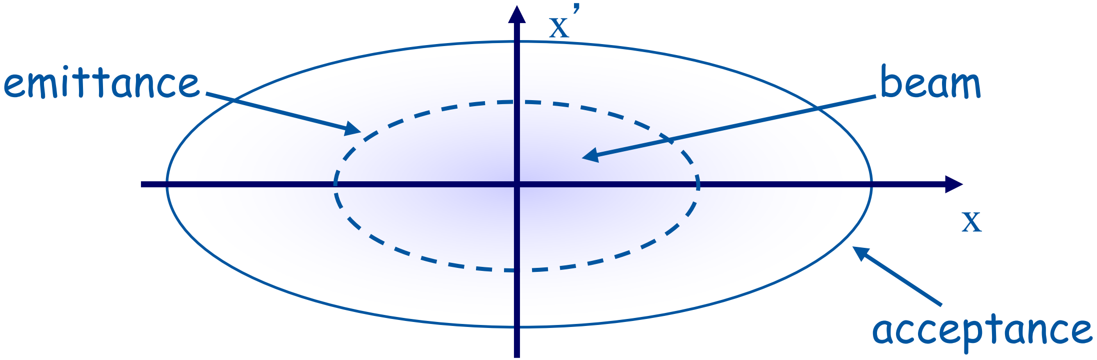
Vertical Phase Space

Phase Space Ellipse Rotation



Transverse Emittance

- Observe all the particles at a single position on one turn and measure both their position and angle.
- This will give a large number of points in our phase space plot, each point representing a particle with its co-ordinates x, x'.



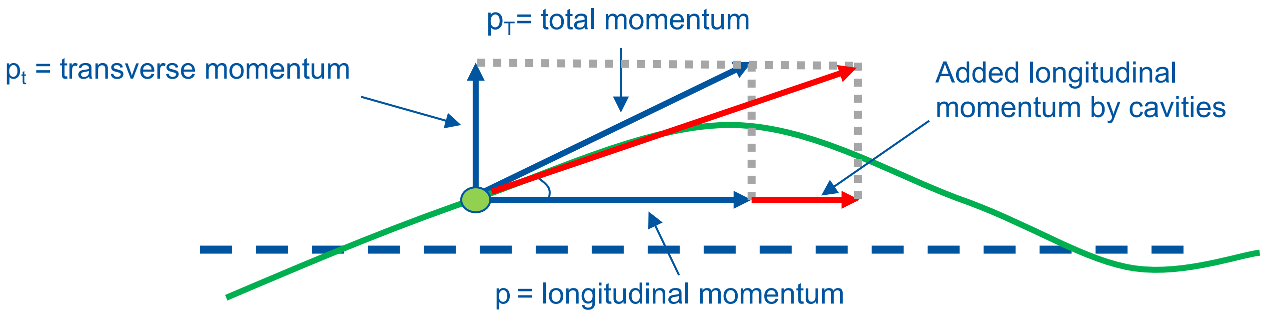
Symbol: ε
Expressed in 1σ, 2σ,..
Units: mm mrad

- The **emittance** is the **area** of the ellipse, which contains all, or a defined percentage, of the particles.
- The **acceptance** is the maximum **area** of the ellipse, which the emittance can reach without losing particles

Adiabatic Damping of the Beam Size

- For the Gaussian definition emittance the rms beam sizes are: $\sigma_x = \sqrt{\beta_x \varepsilon}$ & $\sigma_y = \sqrt{\beta_y \varepsilon}$

- The emittance is constant at constant energy, but accelerating particles will decrease the emittance, which is called adiabatic damping



- To be able to compare emittances at different energies it is normalised to become invariant, provided there is no blow up

$$\varepsilon_x^n = \beta\gamma\varepsilon_x \qquad \varepsilon_y^n = \beta\gamma\varepsilon_y$$

Momentum Compaction Factor

- The change in orbit with the changing momentum means that the average length of the orbit will also depend on the beam momentum.
- This is expressed as the momentum compaction factor, α_p, where:

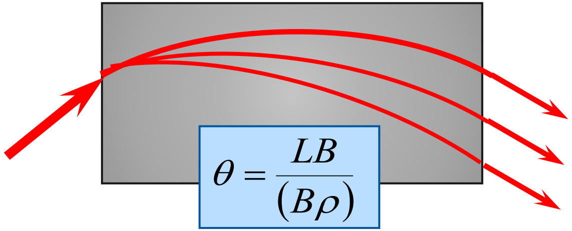
$$\frac{\Delta r}{r} = \alpha_p \frac{\Delta p}{p}$$

- α_p expresses the change in the radius of the closed orbit as a a function of the change in momentum

Dispersion

- Our particle beam has a momentum spread that in a homogenous dipole field will translate in a beam position spread at the exit of the magnet

$$\frac{\Delta p}{p}$$

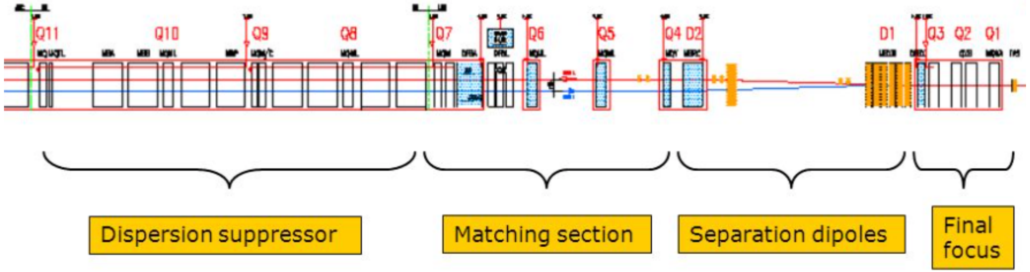


$$\theta = \frac{LB}{(B\rho)}$$

$$\frac{\Delta x}{x}$$

$$\frac{\Delta x}{x} = D(s)\frac{\Delta p}{p}$$

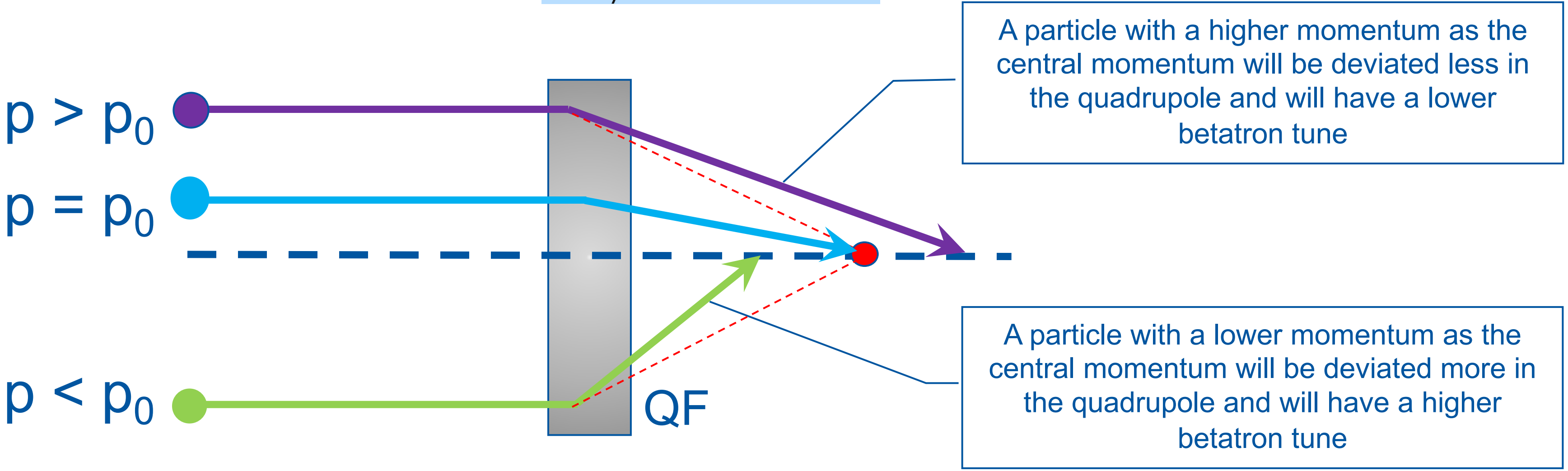
- The beam will have a finite horizontal size due to its momentum spread, unless we install and dispersion suppressor to create dispersion free regions e.g. long straight sections for experiments



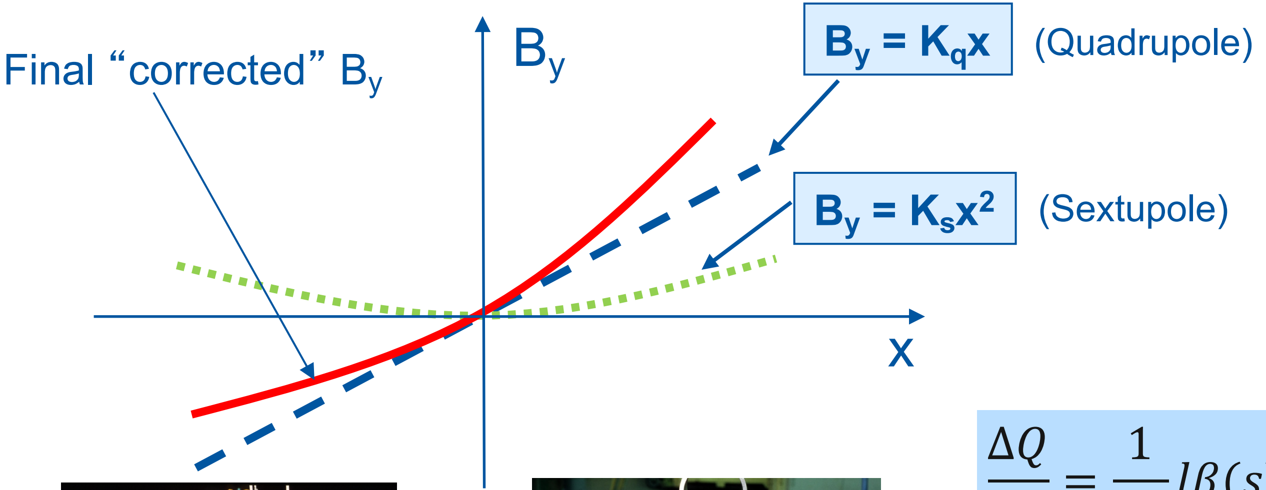
Chromaticity

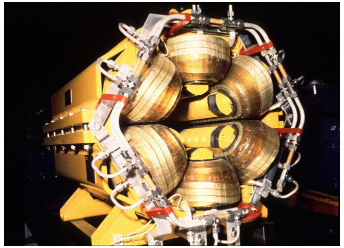
The chromaticity relates the tune spread of the transverse motion with the momentum spread.

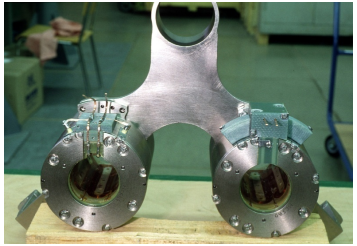
$$\frac{\Delta Q_{h/v}}{Q_{h/v}} = \xi_{h/v} \frac{\Delta p}{p}$$



Chromaticity Correction







$$\frac{\Delta Q}{Q} = \frac{1}{4\pi} \underbrace{l\beta(s)\frac{d^2B_y}{dx^2}\frac{D(s)}{(B\rho)Q}}_{\text{Chromaticity Control through sextupoles}} \frac{\Delta p}{p}$$

Tomorrow Morning More….

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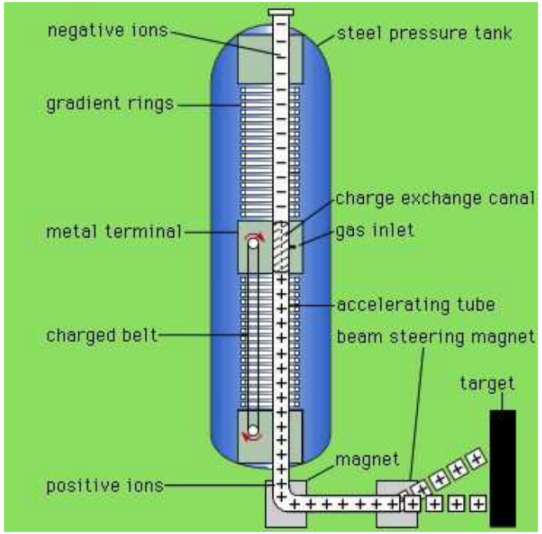
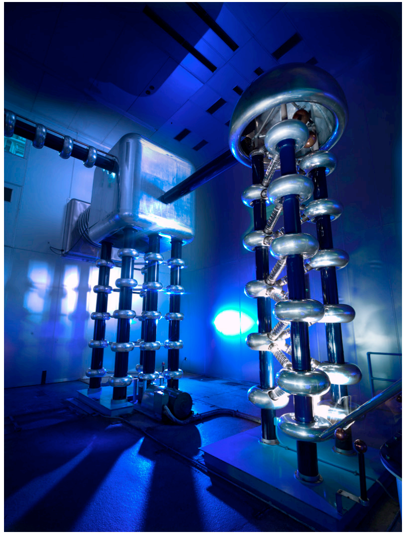
A Very Brief Word on Accelerator History

Cockroft & Walton / van de Graaff

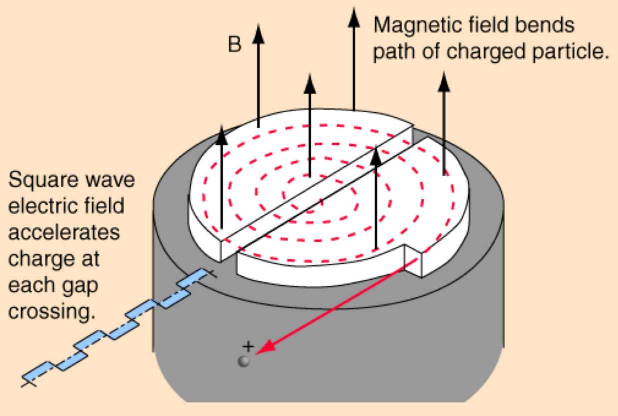
- 1932: First accelerator – single passage 160 - 700 keV
- Static voltage accelerator – limited by the high voltage needed

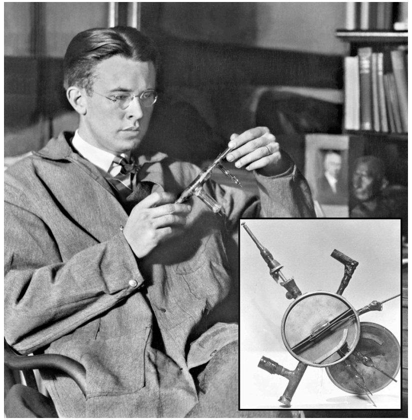




Cyclotron

- 1932: 1.2 MeV – 1940: 20 MeV (E.O. Lawrence, M.S. Livingston)
- E = 80 keV for 41 turns
- Constant magnetic field and alternating voltage between the two D's
- Increasing particle orbit radius
- Development lead to the synchro-cyclotron to cope with the relativistic effects (Energy ~ 500 MeV)

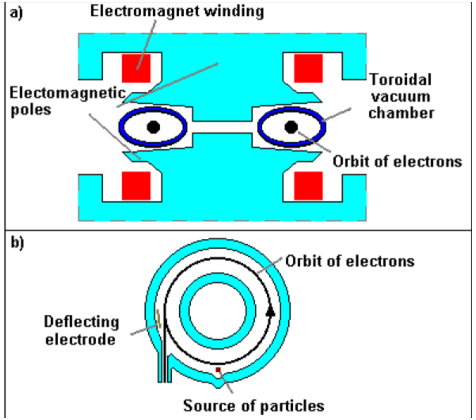




In 1939 Lawrence received the Noble prize for his work.

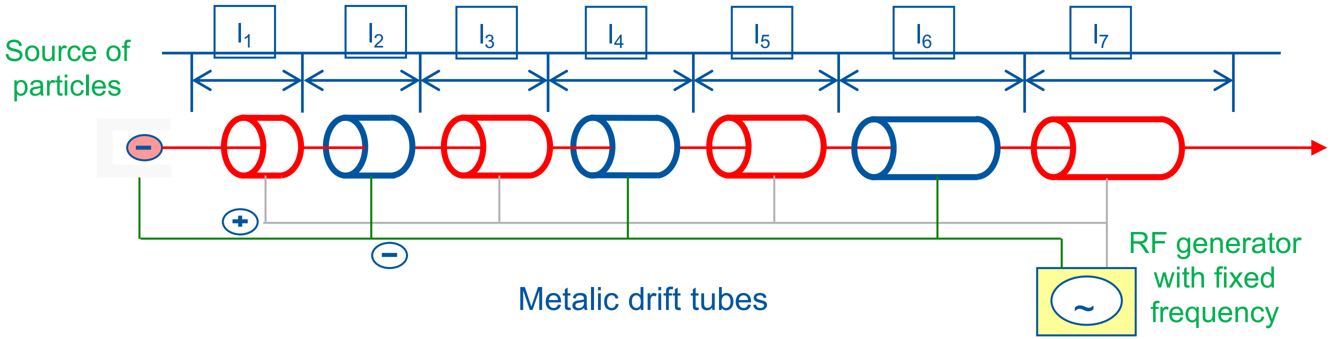
Betatron

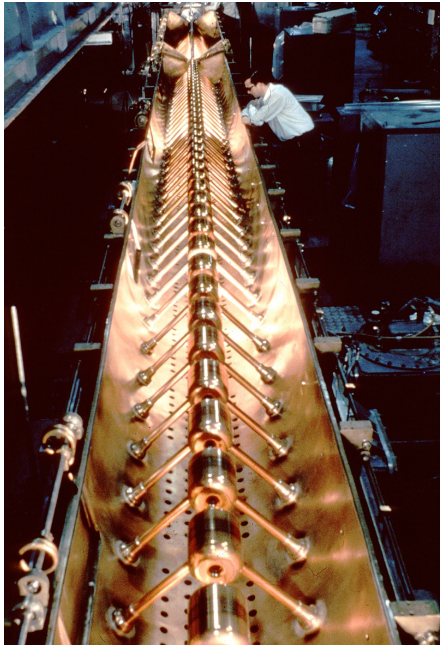
- 1940: Kerst 2.3 MeV and very quickly 300 MeV
- First machine to accelerate electrons to energies higher than from electron guns
- It is actually a transformer with a beam of electrons as secondary winding
- The magnetic field is used to bend the electrons in a circle, but also to accelerate them
- A deflecting electrode is used to deflect the particles for extraction.



Linear Accelerator

- Many people involved: Wideröe, Sloan, Lawrence, Alvarez,….
- Main development took place between 1931 and 1946.
- Development was also helped by the progress made on high power high frequency power supplies for radar technology.
- Today still the first stage in many accelerator complexes.
- Limited by energy due to length and single pass.





Synchrotrons

- 1943: M. Oliphant described his synchrotron invention in a memo to the UK Atomic Energy directorate
- 1959: CERN-PS and BNL-AGS
- Fixed radius for particle orbit
- Varying magnetic field and radio frequency
- Phase stability
- Important focusing of particle beams (Courant – Snyder)
- Providing beam for fixed target physics
- This invention paved the way to today's colliders